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Study of Biogas Production From Palm Oil Solid Wastes: A Review

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ABSTRACT

In 2021 Indonesia currently provides 58% of global crude palm oil, resulting in enormous amounts of oil palm wastes. The purpose of this research is to determine which palm oil solid waste has the potential to be used as a substrate for biogas production, and what is the optimum method and parameter to produce an economically viable source of biogas. The method used for this research was by means of literature review, in which the data used were acquired from journals, thesis, reports and research papers. This research evaluates the different energy potentials of different oil palm wastes which are; Oil Palm Fronds (OPF), Empty Fruit Bunch (EFB), Decanter Cake (DC), Oil Palm Trunk (OPT) and Mesocarp Fibre (MF). Which resulted in EFB producing the highest yield of methane (429 mL CH_4/g VS) at similar operating parameters and methods. The optimization of methane yield from the substrates were studied using different methods and operating parameters resulting in the highest methane yield of 617 mL CH_4/g VS from co-digestion of DC + POME. Although, considering the economic viability; it was found that OPF as the waste from bioethanol production was most preferable, not only producing biogas but also bioethanol. It produced a high methane yield of 514 ml CH_4/g VS at lower operating cost.

Keywords: *Biogas, Oil palm solid waste, OPF, Anaerobic digestion, Waste to energy*

1. INTRODUCTION

The global energy consumption has increased up to 2.3% in the year 2018 to meet the ever-increasing energy demand (1). Fossil fuel as the leading source of fuel covering up to 81% of the total energy growth in 2018. As renewable energy still struggles to meet the increasing demand for electricity worldwide (2).

The rapid rise in the global energy demand is due to the economic and population growth, most evidently from large emerging countries which is estimated to account for 90% of the energy demand in the year 2035 (2). Although, even with the introduction of renewable energies, fossil fuels remain as the primary source of energy covering up to 85% of the total energy supply (3).

The global demand for crude oil increases by 2% each year and it is only a matter of time before there will be shortages of oil. Based on the 'Hubert's peak' and 'The Big Rollover' crude oil will be depleted around the year 2060 – 2070 (4). Furthermore, not only are fossil fuels and crude oils depleting, they also emit 78% of the global greenhouse gas emissions (5).

With the growing concerns of global warming and scarcity of energy sources, the replacement of fossil fuels is inevitable. The renewable source of energies is growing at a rapid rate contributing to as much as half of the global energy supplies. It is estimated that by the year 2040 it will become the largest power source worldwide (6). Alternative renewables such as biogas and bio-methane are the fastest forms of bioenergy with a cumulative market share which totals from 5% to 12% by the year 2040 (7).

Biogas is a clean and renewable source as it does not produce pollution and helps reduce the greenhouse gas emissions (8). It utilizes organic matters such as animal manure, crop waste, organic wastes from restaurants, and factories that uses fermentation process as raw materials (9).

Indonesia has been the largest palm oil producer in the world with 58% of the global palm oil production in the year 2021 (10). This leads to an equally large amount of bio wastes such as oil palm frond (OPF) and oil palm trunk (OPT) during replanting. The conversion from Fresh Fruit Bunch (FFB) to Crude Palm Oil (CPO) further produces wastes from the palm oil mills, wastes

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such as Palm Kernel Shell (PKS), Mesocarp fiber (MF), Palm Oil Mill Effluent (POME) and Empty Fruit Bunch (EFB) (11).

Currently the energy production is still dominated by fossil fuels contributing to around 80% of the global energy mix which accounts to around three quarters of the global greenhouse gas emissions. The solution to these problems is to shift to more low carbon-sources of energy; renewable energy such as bioenergy which includes biogas (12).

Utilizing this biomass as a substrate for biogas production is beneficial because it reduces the total biomass waste from Crude Palm Oil production. Biogas production is dependent on different parameters that need to complement each other to produce better biogas primarily from the four broad areas of feedstock utilization which consists of the substrate, inoculum, temperature, pH, pre-treatment and co-digestion (13).

Biomass are renewable organic materials that are derived from animals and plants. It contains energy stored that came from the sun. It is estimated that 146.7 million tons of biomass every year is produced in Indonesia. That is equivalent to around 470 GJ/year. The majority of the biomass share is from rice residues with an energy potential of 150 GJ/year, rubber wood with 120 GJ/year and Palm oil residues with 67 GJ/year (14). Currently the use of Biogas in Indonesia is just around 4% and the Government plans on renewable energies to be 23% by the year 2025. According to the data from Indonesia Palm Oil Association (GAPKI) the biomass production from the Palm Oil Industry is around 182 million tons of dry matter and 4127 million m^3 of biogas can be produced using 147 million tons of Palm Oil Mill Effluents (POME). This potential in biogas is enough to encourage Indonesia to utilize palm oil wastes as the biomass source for renewable energies.

In Indonesia, throughout the years of 1980 to 2015 the land use of oil palm plantation had a steady growth of 14.26% every year starting from 294,560 to 11,300,370 hectares. This increase in land usage could only be the result of an increase in demand and production of palm oil. Palm oil production grew by an average of 17.46% every year, from 849,121 tons to 37,541,157 tons (15). This can be seen from the graph given in figure 1.

Methanogenic archaea produce biogas while reacting with the biodegradable materials in an anaerobic condition. The compositions of a typical biogas are 48 to 65% methane (CH_4), 36 to 41% carbon dioxide (CO_2), and some trace gasses like hydrogen, nitrogen, hydrogen sulfide. With biogas being able to produce up to 65% methane gas, it is a great renewable source of clean energy (16).

Methanogens or methane producing archaea, are the last in a chain of microorganisms, which degrade organic material and return the decomposition matter to the environment. During the process of decomposition, biogas will be produced. Biogas utilizes biomass as raw material therefore it is a non-fossil gas. Biomass/organic matters from sewage, manure, landfills or food industry waste all have the potential to be converted to biogas. Biogas will then be produced through anaerobic fermentation. It is a renewable source of energy that can be used as fuel for cooking, lighting, running vehicles, generators, and many more.

Anaerobic digestion is a multistep chemical and biological process that uses biomass as a source of energy. For the complete transformation of biomass waste into biogas, it will have to go through the complete anaerobic digestion process which includes several stages; beginning with hydrolysis, acidogenesis/fermentation, acetogenesis and methanogenesis. Throughout the whole process, complex organic polymers that form the biomass are broken down to smaller molecules through the use of microorganisms and chemicals. After completing the anaerobic digestion process, the biomass would have been converted to biogas which are mainly made up of carbon dioxide and methane along with wastewater.

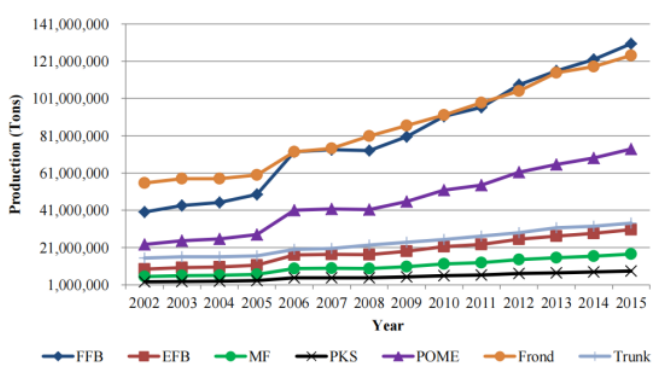

Figure 1 Graphic representation of the development of palm oil production and plantation coverage in 1980 – 2015 (15).

2. BIOGAS PRODUCTION FOR PALM OIL SOLID WASTES

From studying multiple literatures about the different oil palm solid waste, it was found that Oil palm frond (OPF), Empty Fruit Bunch (EFB), Decanter Cake (DC), Oil Palm Trunk (OPT) and Mesocarp Fibre (MF) all have the potential to produce biogas. Different methods of biogas production were studied using different substrate co-digestion, operating pH and temperature, type of inoculum, duration and pretreatment. The method in which the substrate of DC and POME were co-digested resulted in the highest overall methane yield. Although economic viability was taken into consideration, the optimum method of biogas production was the result of using OPF from bioethanol waste as substrate for biogas production.

2.1. Oil Palm Solid Wastes

The palm oil industry produces exceptionally large amounts of wastes during harvest, replanting and processing. Currently, only 10% of oil palm biomass residues are used as a bio composite as raw material for industrial use or as a replacement of raw materials for wood. Oil palm waste with lignocellulose content can be used to make biomaterials as reinforcement in both traditional and advanced bio composites.

In 2017, E.Hambali and M.Rivai from Indonesia, made research with the topic : "The Potential of Palm Oil Waste Biomass in Indonesia in 2020 and 2030" (17). The research discussed that oil palm wastes will continue to rise due to the increasing demand of crude palm oil. In 2020, 37,816,105 tons of EFB, 21,560,251 tons of MF, 10,389,975 tons of PKS, 91,224,865 tons of POME, 128,914,621 tons of frond, and 59,722,455 tons of trunk will be generated. Total output in 2030 is expected to be 53,904,512 tons EFB, 30,732,801 tons MF, 14,810,264 tons PKS, 130,035,387 tons POME, 128,914,621 tons frond, and 59,722,455 tons trunk. This makes a total of 418,120,040 tons of palm oil waste and from that; 68.90% are in the form of solid wastes which amounts to 288,084,653 tons. The potential of these solid and liquid wastes is huge. Developing ways to utilize them are being done. There are currently many ways to utilize these wastes for example; Mesocarp fibre (MF) and Palm kernel shells (PKS) are commonly used as boiler fuel, and processed as bio pellets. Oil palm frond, empty fruit bunch and oil palm trunk are used as mulching material and raw materials for industrial uses. Palm oil mill effluent (POME) is currently the most developed for biogas production, while the majority of the other wastes in the form of solid wastes are still undeveloped and further study is required. The graph shown in figure 2 shows the graph of Indonesia's production of oil palm wastes.

In 2017, EU-Malaysia Chamber of Commerce and Industry (EUMMCCI), published a literature about the oil palm biomass and biogas in Malaysia. Oil palm biomass wastes are categorized into two which are; liquid and solid. Both of these types of biomass are the result of extracting oil from oil palm. The oil palm biomass consists of different components which are: oil palm frond (OPF), empty fruit bunch (EFB), decanter cake (DC), oil palm trunk (OPT), mesocarp fibers (MF), palm kernel shells (PKS) and oil palm mill effluent (POME). Each component has different potential and utilization. In the year 2011 The palm oil industry in Malaysia produced approximately 80 million tons of solid biomass and 60 million tons of liquid biomass (POME) and are still predicted to grow over the coming years. From all types of palm oil biomass only palm oil mill effluent (POME) has been utilized and commercialized for methane production while the majority of the other wastes are yet to be developed. Detailed utilization of oil palm wastes in Malaysia can be seen in table 2.1.

2.2. Oil Palm Frond (OPF)

Evidently, from citing multiple literature it was found that OPF has the potential to be a substrate for the production of biogas; by means of different anaerobic digestion methods and parameters. These parameters include the co-digestion of substrates, type of inoculum, operating temperature, operating pH and methods of pretreatment.

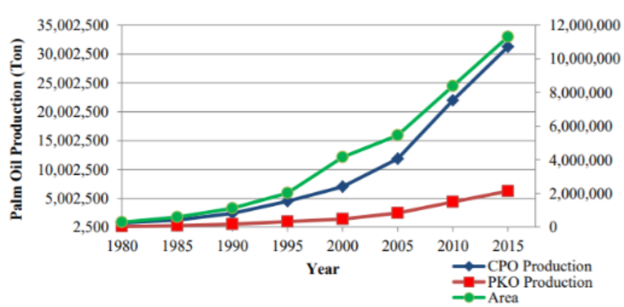

Figure 2. Projection of Indonesia's palm oil waste production for 2016-2030

Table 2.1. Palm oil biomass-based products and their commercial stage in Malaysia (2011)

Table 2.1 Palm Oil Biomass-based products and their Commercialization Stage in Malaysia (2011).

	Pellets	Biofuel	Biogas	Green Chemicals	Biofertiliser	Biochar	Biocomposites	Other
Empty fruit bunch (EFB)	EFB Pellets	Bioalcohol	Syngas	Industrial Sugars/Chemical	Organic Compost	Carbon Fibers	Fibreboard	Pulp Fibremat
Palm kernel shells (PKS)	Coal substitute					Activated Carbon		
Trunkc (OPT)	OPT Pellets	Bioalcohol	Syngas	Industrial Sugars/Chemical	Organic Compost	Biochar	Engineered Lumber	
Fronds (OPF)	OPF Pellets	Bioalcohol	Syngas	Industrial Sugars/Chemical	Organic Compost	Biochar		Phytochemicals
Palm kernel cake (PKC)	PKC Pellets			Biopolymers				Animal Feed
POME		Bioalcohol	Methane	Biopolymers	Organic Compost			

= Commercialised = Development Stage = Potential

Table 2.2.1. Srirnachai Tussanee and friends' research (21)

Materials			
OPF (bioethanol effluent)			
Pre-treatments Methods			
Parameters	Range of Study	CH_4 yield (ml CH_4/g VS)	Optimum condition
Substrate	Water + Microwave	514	Water + Microwave
	Sulfuric acid (1%) + Microwave	379	
	Sulfuric acid (2%) + Microwave	477	
	Sulfuric acid (3%) + Microwave	473	
	Sulfuric acid (4%) + Microwave	495	
	Hydrogen Peroxide (1%) + Microwave	333	
	Hydrogen Peroxide (2%) + Microwave	425	
	Hydrogen Peroxide (3%) + Microwave	387	
	Hydrogen Peroxide (4%) + Microwave	484	

Substrates used for biogas production can vary. OPF is used as the main biomass for substrate. From Wantanasak Suksong's research (18) it shows that OPF as a substrate alone with POME as inoculum has the potential to produce methane; as observed in table 2.2.2. The co-digestion of OPF with other biomass as substrate could be beneficial in increasing methane production. Based on Immega Adelia Nurdin and friend's research (19), the co-digestion of OPF and cow manure has the potential to produce biogas. It showed that a decrease in the pH and weight during the anaerobic digestion indicated that microbial activity took place. Ossai and Ochonogor Samuel's research (20) compares the methane production between OPF substrate alone and the co-digestion of OPF and cow manure. The co-digestion of OPF and cow manure resulted in an increase of methane production by 29%, which indicates that synergism between the two types of biomass took place. OPF in the form of waste effluent from fermenting OPF into bioethanol shows great potential to be used as a substrate for methane production as discussed in Srinachai and friend's research (21). Producing the highest methane yield of 514 ml CH_4/g VS as seen in table 2.2.1.

Inoculum used can vary from one digester to the other. It was found that Cow manure and POME sludge are the most common inoculum used for producing biogas from OPF. POME sludge was the better inoculum due to its nature of having microorganisms that are fit for the degradation of oil palm wastes; since POME is also another form of palm oil waste. It is also widely known to have good potential for biogas production, hence it's prominent use in the production of biogas from Oil palm biomasses.

Temperature affects the rate of fermentation as it determines the inoculum's (microorganisms') environmental conditions. Different types of microorganisms require different ranges of temperature to operate. This research shows that the operating temperature for the digestion of OPF were at 35 oC (mesophilic) and 55 ºC (thermophilic). In the study of Wantanasak Suksong (18) OPF digested at the temperature of mesophilic and thermophilic were compared and showed that thermophilic temperature produced a higher average methane yield up to 129% more than mesophilic temperatures.

The pH regulates the alkalinity or the acidity of the anaerobic digestion. The pH is important because too high or too low of a pH will result in the degradation of the microorganisms. The ideal pH for methanogenic bacteria was found to be around the neutral pH of 7. Some of the inoculums and substrates are carefully adjusted to the ideal pH through the use of acidic or basic chemicals. A drop in pH levels after a few days of digestion is normal due to the production of volatile fatty acids (VFA) during the process known as acidification. Based on Ossai and Ochonogor Samuel's research (20), pH can also be a good indication for methanogenic activity, as a drop in pH can indicate that the conversion to VFA for methanogenic bacteria is occurring. How sharp the drop in pH could indicate a more intensive conversion of VFA.

Different methods of pretreatment were used for the production of biogas. Physical pretreatment by crushing, sieving or grinding to reduce size are the most commonly used pretreatment. Other methods such as thermal pretreatment, sun drying and chemical pretreatment are used. From Monica Perdhani Putri's research the use of pre-treatment for OPF co-digested with EFB produced a slight increase in methane production during anaerobic digestion. Based on Srirnachai Tussanee and friends' research (21) it was found that using size reduction and co-pretreatment using water and heat produced the best methane yield. The co-pretreatment using water and microwave is advantageous as it had low corrosion and toxicity, compared to using other chemicals; as seen in table 2.2.1.

Table 2.2.2 Wantanasak Suksong and friends' research (18)

Solid State Anaerobic Digestion of OPF				
Parameters	Range of Study			Optimum condition
	S/I	Thermophilic	Mesophilic	
		Methane yield (ml CH_4/g VS)		
Feedstock to Inoculum Ratio at thermophilic and mesophilic conditions	2:1	89.8	46.7	S:I ratio of 3:1 at thermophilic conditions
	3:1	102.2	44.5	
	4:1	83.6	43.0	
	5:1	01.4	12.7	

Table 2.2.3 Summary of Oil Palm Frond (OPF) for methane production

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref
OPF + EFB (TS 8%)	Wet anaerobic co-digestion	Size reduction and NaOH 5%	Cow Manure	35	7±0.0	25	670 ml CH_4*	(39)
OPF + Cow manure	Solid anaerobic Co-digestion	Size reduction, Sun drying and pre-fermentation	ND	35	7±0.0	27	9.33 ml CH_4/g VS	(20)
OPF ethanol effluent (<10%TS)	Wet anaerobic digestion	Size reduction and Co pretreatment: Water + Microwave	POME sludge	35	7.3 - 7.5	ND	514 ml CH_4/g VS	(21)
OPF (TS 16%)	Solid State Anaerobic mono-digestion	Oven dried (95°C for 48 h), Size reduction (5mm)	POME sludge	55	7±0.0	20	207 ml CH_4/g VS	(18)

As can be seen from the table 2.2.3, OPF as substrate can be converted into biogas at different variations of methods and combinations of parameters. OPF can be co-digested with other biomass to compensate for the characteristic it lacks in the production of methane. By comparing different sources of literature, it was found that the effluent from OPF that has gone through the pretreatments of size reduction and water + microwave then through simultaneous saccharification produced the highest methane yield. By means of wet anaerobic digestion with inoculum as POME plant sludge at operating temperature of 35 °C for an unspecified number of days. The methane yield was 514 ml CH_4/g VS.

2.3. Empty Fruit Bunch (EFB)

Different methods of biogas production using EFB as substrate was seen from different literatures. Anaerobic digestion of EFB shows that it has the potential for biogas production by setting different methods and parameters. The parameter for anaerobic digestion of EFB were broad, which includes;

The main substrate used for study is EFB. Based on Muthita Tepsour and friends (22) and Vincentius' research shows that anaerobic digestion of EFB alone has the potential to produce methane. Co-digestion of EFB with other substrates can result in synergism or antagonism. From Muthita Tepsour's research (22), it showed that the co-digestion of DC and EFB caused antagonism in the biogas production; resulting in lower methane yield. Although when EFB was co-digested with POME it resulted in synergism which increased the methane production based on Sittikorn Saelor's research (23). Based on Rosa's research (24), EFB has a low potential to produce biogas, but when co-digested with cow manure; the methane yield increased by almost 50%. Other research also shows that co-digestion of EFB with sewage sludge, POME and cow manure have the potential for the production of methane.

The variety used for the study of EFB includes sludge, POME, cow manure and a combination of sludge and inoculum. POME and anaerobic sludge have been shown to be a viable source of inoculum. From Vincentius' research, biogas sludge and wastewater sludge as inoculum were used to evaluate the effects of different inoculums on methane production. It shows that biogas sludge produced higher methane compared to wastewater sludge, indicating that different inoculums have different effects on methane production. When these inoculums were used during anaerobic digestion, sufficient amount of substrate to inoculum is required to avoid excessive pH spikes especially during the acidification stage.

Muthita Tepsour's research (22), as can be seen in table 2.3.1 shows that EFB digested at the temperatures of 55 °C and 35 oC were compared and concluded that the anaerobic digestion at higher temperatures of 55 °C performed better and resulted in higher methane production. The effect of the temperature on methane yield varied depending on the S:I ratio studied and percentage of OPA studied. The temperature increase affected the methane yield in different intensities. From an increase of around 16% up to an increase of 650% in methane yield. This is because thermophilic conditions are more favourable for acidogenesis and hydrolysis as discussed in the research. Although during co-digestion of substrates it is advised to use mesophilic temperatures as it is more flexible to adjustments. It was also found that temperature can have an effect on pH as the addition of a buffer was required during thermophilic temperature and no buffer was needed during mesophilic temperatures. Nicholas Agustianne's research further supports this. By anaerobic digestion at a higher temperature of 45 oC, a greater methane yield was observed compared to that of 35 ^{o}C by around 82% more.

Evidently from the compilation of research it was found that the ideal pH of anaerobic digestion was within the neutral range of 7 pH. It is ideal to have a neutral pH because the methanogenic bacteria operate best at an environment with a neutral pH, consequently a pH higher or lower than 7 can damage the microorganisms resulting in the decrease of methane production or kill the microorganism resulting in the crash of the anaerobic digestion process. It can be further supported by Muthita Tepsour's research that the addition of OPA as buffer was helpful in regulating the pH especially during the acidogenesis and acetogenesis stage where a spike in pH happens.

From Pornwimon's research about pretreatment of EFB (25) as seen in table 2.3.2, the effects of single pretreatment methods to methane production were studied. It shows that a single pretreatment method of size reduction produced higher methane compared to single pretreatments using NaOH, bio-scrubber effluent and AS. The use of chemicals for pretreatment only increases the methane production by around 30% while size reduction increased by 90%. The use of combining pretreatments was studied in Nicholas Augistianne's research; which resulted in the increase of methane yield when size reduction, thermal pretreatment and chemical pretreatment by NaOH were applied. This indicates that different methods and combinations of pretreatments have a varying effect on the methane production.

Table 2.3.3 about EFB seen above proves that EFB can be utilized as a substrate for biogas production. Different parameters produced unique methane production. It was observed that EFB can be co-digested along with other substrates that could allow better methane production. The comparison of different literatures showed that EFB anaerobically digested for 35 days at 55 oC that had gone through a size reduction pretreatment produced the highest methane yield of 429 ml CH_4/g VS.

2.4. Decanter Cake (DC)

There are several methods to produce biogas using DC as substrate. Fermentation by anaerobic digestion is the most common method of producing biogas. The process involves the digestion of DC through microbes in anaerobic environment. The parameters at which it operates vary. Some parameters that affect the anaerobic digestion process include;

Table 2.3.1 Summary of Muthita Tepsour, Nikannapas Usmanbaha and friends' research (22)

Digestion Method	Temperature (^{o}C)	Optimum Condition for Methane yield
Solid-state mono-anaerobic digestion of EFB	55	S:I ratio of 2:1 and OPA of 10% = **375 ml CH_4/g VS**
	35	S:I ratio of 2:1 and OPA of 10% = **25 ml CH_4/g VS**
Solid-state mono-anaerobic digestion of DC	55	S:I ratio of 3:1 and OPA of 5% = **160 ml CH_4/g VS**
	35	S:I ratio of 3:1 and OPA of 5% = **50 ml CH_4/g VS**
Solid-state co-anaerobic digestion of EFB and DC	55	S:I ratio of 3:1, EFB:DC ratio of 19:1= **353.8 ml CH_4/g VS**
	35	S:I ratio of 3:1, EFB:DC ratio of 19:1= **288.1 ml CH_4/g VS**

Table 2.3.2 Summary of Pornwimon Wadchasit, Chairat Siripattana and Kamchai Nuithitikul's research (25).

Pretreatment				
Parameters	Range of Study	Percentage methane (%)	Methane yield (ml CH_4/g VS)	Optimum condition
Type of pre-treatment	No pretreatment	50.3	226.0	Size reduction
	Size reduction	52.7	429.0	
	3% NaOH	51.2	324.1	
	5% NaOH	52.4	314.6	
	7% NaOH	52.9	345.5	
	Bio-scrubber effluent	51.6	326.4	
	AS	50.9	297.3	

The main substrate used for this study is DC. Based on the study of Suwimon and Nipon's research (26) DC has the potential to produce methane as an individual feedstock/substrate. Muthita Tepsour's research (22) supported that anaerobic mono-digestion of DC has the potential to produce methane of 160 ml CH_4/g VS. By co-digesting it with EFB the methane yield increased to 353.8 ml CH_4/g VS, which is a 121% increase in methane yield. Other co-digestion of DC with EFB, POME, waste water and sewage sludge have the potential to increase methane production. As discussed in N. Khairul Anuar's research (27) the characteristics of Sewage Sludge has high Nitrogen content but low in Carbon, while DC has high Carbon content but low Nitrogen content. By co-digesting both substrates, it benefits each other by making an ideal composition for anaerobic digestion; increasing the methane yield by 8%. Karaket Wattanasit's research (28) as seen in table 2.4.1, studied the effects of co-digesting DC to POME at varying percentages. It showed that by co-digesting DC+POME increased by a minimum of 55% in methane yield, further optimization showed that by co-digesting DC (30%) +POME (70%) resulted in an increase by around 108% in methane yield when compared to the mono-digestion of DC.

A variety of inoculum were used for the inoculation of decanter cake. Using different types of sludge from POME, anaerobic biogas, waste water and a combination of POME + biogas. in N. Khairul Anuar's research (27) shows the effect of inoculum comparing different S/I ratios which include a study without the use of inoculum. It showed that without inoculum the methane production will be low, although too much inoculum can also hinder the methane production.

The temperature affected the methane production of DC based on the literature by SJ Malik (29) that around 46% more methane was yielded during 38°C compared to 26oC. It was further supported by Muthita Tepsour's research (22) which uses the temperature of 55 oC and 35 °C where DC digested at 55 °C resulted in a higher methane yield compared to 35 °C by 110%. This shows that an increase in temperature can increase the methane production.

It was also found that the ideal pH of anaerobic digestion was within the neutral range of 7 pH. It is ideal to have a neutral pH because the methanogenic bacteria operate best at an environment with a neutral pH, consequently a pH higher or lower than 7 can damage the microorganisms resulting in the decrease of methane production or kill the microorganism resulting in the crash of the anaerobic digestion process. It can be further supported by Muthita Tepsour's research that the addition of OPA as buffer was helpful in regulating the pH especially during the acidogenesis and acetogenesis stage where a spike in pH happens.

The pretreatment of DC was done in different methods. Based on the research by Thaniya Kaosol (30), the DC that has gone through oven pretreatment produced a higher methane yield compared to un-pretreated DC by around 25%. This was further supported by Chonticha Rongwang's research (32) as seen in table 2.4.2, showed that the use of ozone pretreatment increased the methane yield by around 24 – 52 % and thermal pretreatment increased by 3% - 9% compared to untreated DC. This shows that different methods of pretreatment of DC can potentially increase the methane production.

Table 2.3.3 Summary of Empty Fruit Bunch (EFB) for methane production

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref
EFB + SCS (95:5)	Solid State anaerobic co-digestion	Oven dried, grinded to 5mm,	Methane production sludge enriched + POME	35	7±0.0	50	18.2 ml CH_4 /g VS	(40)
EFB + 10% OPA	Solid State Anaerobic mono-digestion	Pressurized steam (145°C), drying (105°C), Size reduction <2mm	Anaerobic sludge + POME	55	7±0.0	60	375 ml CH_4/g VS	(22)
EFB + DC (19:1)	Solid State Anaerobic co-digestion	Pressurized steam (145°C), drying (105°C), Size reduction <2mm	Anaerobic sludge + POME	55	7±0.0	60	353 ml CH_4/g VS	(22)
EFB (2g VS/L) + POME (2g VS/L)	Anaerobic co-digestion	Shredding (0.5 cm)	ND	35	7±0.0	30	323 ml CH_4/g VS.	(23)
EFB + CM	Anaerobic co-digestion	Size reduction (2cm)	Cow manure	Ambient temp.	7±0.0	80	114 ml CH_4/g VS	(19)
EFBMM fed 13 L/day	Anaerobic mono-digestion semi-wet semi-batch	Size reduction (2cm)	Cow manure	35	7±0.0	66	2.43 ml CH_4/g VS	(24)
EFB	Anaerobic mono-digestion	Size reduction, 12% NaOH 100 °C	Biogas Sludge	45	7±0.0	20	161.84 ml CH_4 /g VS	(Nic Agust)
EFB (TS 10-15%)	Solid State Anaerobic mono-digestion	Size reduction	Biogas Sludge	55	7±0.0	35	429 ml CH_4/g VS	(25)
EFB (TS 16%)	Solid State Anaerobic mono-digestion	Oven dried (95°C for 48 h), Size reduction (5mm)	POME sludge	55	7±0.0	20	223 ml CH_4/g VS	(18)
EFB (TS 25%)	Solid State Anaerobic mono-digestion	Oven dried (95°C for 48 hours), Size reduction (5mm)	POME sludge	37	7±0.0	45	144 mL CH4/g VS	(35)
EFB	Anaerobic mono-digestion	Size reduction (1-5cm)	Anaerobic methanogenic bacteria sludge	55	7±1.0	40	211.7 mL CH4/g VS	(25)

As can be seen from the table 2.4.3, DC as substrate can be converted into biogas at different variations of combinations of parameters. DC can be co-digested with other substrates to balance the characteristic it lacks for methane production. By comparing different sources of literature, it was found that the anaerobic co-digestion of DC+POME that has gone through the pretreatments of size reduction, using inoculum as biogas sludge at operating temperature of 60 °C. The methane yield of this specific method is 613 ml CH_4/g VS.

Table 2.4.1 Summary of Karaket Wattanasit, Kasem Asawateratanakil and Sompong O-thong's research (28)

Anaerobic co-digestion			
Parameters	Range of Study (%)	Methane Yield (ml CH_4/g VS)	Optimum condition
Percentage of POME and DC	50/50	549.0003	Co-digestion of 70% POME + 30% DC
	60/40	518.8853	
	70/30	613.0026	
	80/20	544.6697	
	90/10	426.246	
	100	472.9005	

Table 2.4.2 Summary of Chonticha Rongwang, Supawadee Polprasert and Suwimon Kanchanasuta's research (32)

Pretreatment			
Parameters	Range of Study	Methane yield (ml CH_4/g TS)	Optimum condition
Type of pre-treatment	No pretreatment	382.38	Ozone 60 min
	Ozone pretreatment 20 min	476.37	
	Ozone pretreatment 60 min	580.63	
	Thermal pretreatment 30 min	393.69	
	Thermal pretreatment 60 min	417.65	

2.5. Oil Palm Trunk (OPT)

OPT was found to be a viable substrate for biogas production by anaerobic digestion. From multiple literatures about OPT, it showed that operating temperature, operating pH, co-digestion of substrates, type of inoculum and methods of pretreatment affected the production of biogas.

The main substrate used for this study is OPT. Based on the research from Wantanasak Suksong (18), OPT is capable of mono-digestion with POME as inoculum. This was further supported by Sisrsuda Chaikitkaew (33) where it shows OPT with the inoculum of anaerobic sludge granules has the potential to produce methane. OPT that is in the form of effluent from the production of bioethanol produced a higher methane yield compared to raw OPT. Co-digestion shows a viable production of methane based on Tanawut Nutongkaew (34) where OPTr was co-digested with POME.

The inoculum used were POME, anaerobic sludge and a combination of both. Based on Wantanasak Suksong (18) different S/I ratio shows to have an effect on the methane production, where 3:1 ratio resulted in a better methane yield. It further showed that without the presence of an inoculum the methane production will be low, although too much inoculum can also hinder the methane production.

The temperature effects the methane yield based on Wantanasak Suksong research (18). During thermophilic temperatures; the methane yield is around 12% more compared to during mesophilic temperatures for the mono-digestion of OPT, as seen in table 2.5.1.

The ideal pH of anaerobic digestion was found to be at the neutral pH of 7. It is the most ideal for the methanogenic bacteria to grow. An increase or a decrease in the operating pH can damage the bacteria, which can hinder the production of methane therefore stopping the process of anaerobic digestion.

The pretreatments used were all different from one another, but size reduction has been shown to be one of the most important methods of pretreatment as it is present in most methods of anaerobic digestion. Based on Tanawut Nutongkaew's research (24) that the application of enzyme pretreatment increased the methane yield by around 4% compared to untreated substrate. Although it was also found that improper pre-treatment resulted in the decrease of methane yield by around 16%. This can be observed from table 2.5.2.

From the table 2.5.3, the optimum method of anaerobic digestion for OPT was found to be by using the co-digestion OPTr and POME hydrolysate, that has gone through a pretreatment of size reduction, sun drying and oven drying. The inoculum used was a mixture of anaerobic seed sludge and POME. The operating pH was 7 at 37 oC for 30 days, which produced a methane yield of 369±6.10 mL CH_4/g VS.

Table 2.4.3 Summary of Decanter Cake (DC) for methane production.

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref
DC+ 5% OPA (TS 15%)	Solid State Anaerobic mono-digestion	Pressurized steam (145°C), drying (105°C), Size reduction <2mm	Anaerobic sludge + POME sludge	55	7±0.0	60	160 ml CH_4/g VS	(22)
DC+EFB	Anaerobic co-digestion	Size reduction	Waste water sludge	37	7±0.0	3	418.9 ml CH_4/g TS*	(26)
DC+ POME	Anaerobic digestion	Size reduction	Biogas sludge	60	7±0.0	45	613 ml CH_4/g VS.	(26)
DC	Anaerobic mono-digestion	Oven dried (95°C) for 48 hours, Size reduction to 3mm	ND	38	7±0.0	21	57 – 72 ml CH_4/g raw material*	(29)
DC + Rubber block waste water	Anaerobic digestion	Size reduction	Methane fermentation stage of UASB from seafood industry	Ambient temp.	7±1.0	100	1673 ml CH_4*	(31)
DC (25% TS)	Anaerobic mono-digestion	Untreated	Sewage Sludge	38±1.00	7±1.0	10	3.25 ml CH_4/g VS.	(27)
DC	Anaerobic mono-digestion	Diluted with water (1:5), Microwaved (169 W for 8 min)	POME sludge	35	7.2 ± 1.0	45	309.9 ml CH_4/g COD*	(31)
DC	Anaerobic mono-digestion	Ozone pretreatment (60 min)	Anaerobic sludge from beverage wastewater treatment	37	7±0.0	35	580.63 ml CH_4/g TS*	(32)
DC (25% TS)	Solid state anaerobic mono-digestion	Oven dried (95°C for 48 hours), Size reduction (5mm)	POME sludge	37	7±0.0	45	128 mL CH4/g VS	(35)

Table 2.5.1 Summary of Wantanasak Suksong, Aminee Jehlee, Apimya Singkhala and friends' research (18)

Solid State Anaerobic Digestion of OPT				
Parameters	Range of Study			Optimum condition
	S/I	Thermophilic	Mesophilic	
		Methane yield (ml CH_4/g VS)		
Feedstock to Inoculum Ratio at thermophilic and mesophilic conditions	2:1	63.5	57.8	S:I ratio of 3:1 at thermophilic conditions
	3:1	63.8	57.1	
	4:1	60.7	51.4	
	5:1	59.1	44.6	

Table 2.5.2 Summary of Tanawut Nutongkaew and friend's research (34)

Enzyme pretreatment			
Crude enzymes from *T. koningiopsis* TM3			
Anaerobic Co-digestion of OPT			
Parameters	Range of Study	Methane Yield (ml CH_4/g VS)	Optimum condition
	Substrate co-digestion		
Co-digestion with and without enzyme hydrolysis 1:1 (v/v)	POME with OPTr (No pretreatment)	355±3.84	POME hydrolysate with OPTr
	POME with OPTr hydrolysate	305±3.85	
	POME hydrolysate with OPTr	369±6.10	
	POME hydrolysate with OPTr hydrolysate	355±0.06	

Table 2.5.3 Summary of Oil Palm Trunk (OPT) for methane production.

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref.
OPT (TS 16%)	Solid State Anaerobic mono-digestion	Oven dried (95°C for 48 h), Size reduction (5mm)	POME sludge	55	7± 0.0	20	161 ml CH_4/g VS	(18)
OPT Acidic effluent from simultaneous saccharification fermentation hydrogen	Anaerobic digestion	Size reduction (10mm), Lime pretreatment (60°C for 121 h)	Anaerobic granule from waste water	35	7.5	ND	6.0 ± 0.4 – 388.5 ± 8.2 mL CH4/g OPT*	(33)
OPTr + POME hydrolysate	Anaerobic co-digestion	Size reduction, Sun dried, Oven dried (68°C), Crude enzyme	Anaerobic sludge + POME	37	7± 0.1	30	369±6.10 mL CH4/g VS	(34)
OPT	Solid Anaerobic digestion	Size reduction (10mm), Lime pretreatment (60°C for 121 h)	Anaerobic granule from waste water	35	7.5	ND	309.4 ± 2.3 mL CH4/g OPT*	(Sitthikitpanya et al., 201

2.6. Mesocarp fiber (MF)

The potential of MF to be a substrate for the biogas production was studied. It was found that MF does have the potential for biogas production through different methods of anaerobic digestion and with different parameters. It was found that co-digestion, inoculum type, pretreatment method, operating temperature, operating pH, and duration of digestion all have individual effects.

The substrate used was mainly from MF. It was found that MF has the potential to produce biogas by anaerobic mono-digestion. Based on Sirsuda Chaikitkaew's research (35) MF with POME sludge as inoculum were able to produce significant amounts of methane of 140 ml CH_4/g VS. It was also observed in Pornwimon Wadchasit's research (25) that showed that MF inoculated with anaerobic methanogenic bacteria sludge was able to produce high methane yields. Co-digestion with another biomass was found to be beneficial. In Mohammed Saidu's research (36) co-digesting MF with CM produced higher methane yield compared to the mono-digestion of MF. This was further supported by M Saidu and friends' research (37). Co-digestion with another type of oil palm solid waste such as EFB was found to be beneficial. In the research by Supanna Chaipa (38), it was found that MF alone has low methane yields but when co-digested with EFB, resulted; in an increased methane production by up to around 8 – 25%. From these literatures, it can be concluded that MF has great potential to be substrate for biogas by means of co-digestion or mono-digestion.

Inoculum used were unique to each method of anaerobic digestion. The inoculums used for MF were POME sludge, biogas sludge, anaerobic methanogenic sludge and waste water sludge. The amount of inoculum used can affect the methane production. Sirsuda Chaikitkaew's research (35), showed that too little inoculum can reduce methane production and too much inoculum can also have the same effect. The balance between the substrate and inoculum are unique to each process of anaerobic digestion.

The effects of temperature on the anaerobic digestion of EFB was studied in Pornwimon Wadchasit's research (25) which showed that during the temperature of 55oC it yielded up to 27% more methane compared when the temperatures were at 40oC. This shows that temperature has an effect on the methane production which can be seen from table 2.6.1.

The ideal pH was found to be neutral at the pH of 7. The operating pH for most if not all of the anaerobic digestion shows that neutral is ideal for the growth and survival of the methanogenic bacteria.

The effects of pretreatment of MF were studied from different literatures. Devin Pathavi researched on the effect of pretreatments on MF and found that alkaline pretreatment resulted in a higher methane production while untreated MF resulted in the lowest methane production. It was also further studied by Mohammed Saidu (36) as shown in table 2.6.2, which supported that mono digestion of MF that was pretreated using biological pretreatment resulted in a higher methane yield compared to untreated MF by up to 161%. When the biological pretreatment of the co-digestion of MF+CM was compared to the untreated MF + CM, the pretreated co-digestion had a higher methane yield up to 115%.

Table 2.6.3 shows the best method to convert MF to methane was found to be pretreating MF by size reduction and inoculated with anaerobic methanogenic bacteria sludge. With operating pH of 7 at the temperature of 55 oC for 40 days. Which produced a methane yield of 269.107 mL CH4/g VS.

2.7. Comparison of substrates at similar conditions

When the methane yield of oil palm solid wastes at similar operating parameters and method were compared, it was found that Empty Fruit Bunch (EFB) had the highest potential of methane yield of 429 ml CH_4/g VS followed by Mesocarp Fibre (MF), Oil Palm Frond (OPF), Oil Palm Trunk (OPT), Decanter Cake (DC) with 269.107 ml CH_4/g VS, 207 ml CH_4/g VS, 161 ml CH_4/g VS and 160 ml CH_4/g VS, respectively. This shows that by altering the method of digestion and the operating parameters the potential of a substrate can significantly increase. DC produced the least amount of methane yield in table 2.7, although in table 2.8 at different methods of anaerobic digestion and operating parameters, it produced the highest methane yield. This shows that the potential of a substrate can drastically increase at the right operating parameters and method used.

2.8. Comparison of oil palm solid waste for methane production

From the five different oil palm solid wastes; Oil Palm Frond (OPF), Empty Fruit Bunch (EFB), Decanter Cake (DC), Oil Palm Trunk (OPT) and Mesocarp Fibre (MF) the best substrate and method used were DC with the highest methane yield of 613 ml CH_4/g VS followed by OPF, EFB, OPT and MF with 514 ml CH_4/g VS, 429 ml CH_4/g VS, 369±6.10 mL CH_4/g VS, and 269.107 mL CH_4/g VS, respectively. The best method for methane production of DC was found to be the co-digestion of DC + POME with a pretreatment by size reduction using an inoculum of biogas sludge with the operating temperature of 60°C and pH of 7 for 45 days. This specific method of anaerobic digestion by utilizing substrate co-digestion, operating temperature, operating pH, duration of digestion and method of pretreatment for the anaerobic digestion of DC has produced the highest methane yield as can be seen on table 2.8. Utilization of two types of waste can be beneficial for the environment and can be an economically viable option. Although, operating at high temperatures at prolonged time can be a disadvantage as it will require higher energy consumption

Table 2.6.1 Summary of Pornwimon Wadchasit, Chairat Siripattana and friends' research (25).

Anaerobic digestion of Mesocarp Fibre				
Parameters	Range of Study		Methane yield (ml CH_4/g VS)	Optimum condition
	S/I	Temperature (°C)		
Effect of Temperature	1:16	40	212.3472	At thermophilic temperature of 55 °C
		55	269.107	

Table 2.6.2 Summary of Mohammed Saidu, Ali Yuzir and friends' research (36).

Biological Pretreatment			
Microorganism	White rot fungi		
Anaerobic co-digestion			
Parameters	Range of Study	Methane yield (ml CH_4/g VS)	Optimum condition
Co-digestion of feedstock	Pretreated MF (3.5 L) + CM (3.5 L) inoculated with POME (1L)	69.3	R1 Pre-treated MF + CM POME with 3.5 L each of both treated MF and CM inoculated with 1 L of POME
	Untreated MF (3.5 L) + CM (3.5 L) inoculated with POME (1L)	32.2	
	Pre-treated MF	12.96	
	Untreated MF	4.96	

If economic viability is considered, the next substrate that had the highest methane yield of 514 ml CH_4/g VS was obtained by wet anaerobic mono-digestion at 35 oC using OPF from bioethanol effluent. Not only does it utilize waste of OPF, it utilizes the waste post bioethanol production from OPF as a substrate for biogas production. Which means that OPF is capable of producing two types of biofuel; bioethanol and biogas as a whole process. It was also found that OPF has the highest total share in oil palm solid wastes, contributing to around 38%. Currently OPF is under-utilized for biofuels as it is mostly used for ruminants or animal feed. Utilization of OPF will increase its added value.

3. DISCUSSION AND CONCLUDING REMARKS

Based on the research done using 30 different literatures, it can be concluded that all types of the studied palm oil solid wastes: Mesocarp Fibre (MF), Empty Fruit Bunch (EFB), Oil Palm Frond (OPF), Oil Palm Trunk (OPT) and Decanter Cake (DC) showed potential as substrate for the production of biogas.

It was found that by anaerobic digestion with similar methods and operating parameters, EFB produced the highest methane yield of 429 mL CH_4/g VS, MF 269 mL CH_4/g VS, OPF 207 ml CH_4/g VS, OPT 161 ml CH_4/g VS, DC 160 ml CH_4/g VS.

By using different methods of digestion and operating parameters, it was found that DC produced the highest methane yield of 613 ml CH_4/g VS with the following conditions: Co-digestion: DC + POME, operating temperature: 60 oC, duration (days): 45, pH: 7, pretreatment: size reduction; and inoculum: biogas sludge.

However, with the consideration of technology and economic; it was found that using Oil Palm Frond (OPF) as the waste from bioethanol production was the most viable and preferable. As it produced a high methane yield of 514 ml CH_4/g VS with lower operating cost based on the operating temperature and duration.

Table 2.6.3 Summary of Mesocarp Fibre (MF) for methane production.

Biological Pretreatment			
Microorganism	White rot fungi		
Anaerobic co-digestion			
Parameters	Range of Study	Methane yield (ml CH_4/g VS)	Optimum condition
Co-digestion of feedstock	Pretreated MF (3.5 L) + CM (3.5 L) inoculated with POME (1L)	69.3	R1 Pre-treated MF + CM POME with 3.5 L each of both treated MF and CM inoculated with 1 L of POME
	Untreated MF (3.5 L) + CM (3.5 L) inoculated with POME (1L)	32.2	
	Pre-treated MF	12.96	
	Untreated MF	4.96	

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref
MF	Solid state anaerobic mono-digestion	Oven dried (95°C for 48 hours), Size reduction (5mm)	POME sludge	37	7±0.0	45	140 ml CH4/g VS	(35)
MF	Anaerobic mono-digestion	Oven dried (105°C for 14 hours), Size reduction, Alkaline pretreatment (4 hours)	Biogas Sludge	35±0.5	7±1.0	21	4170 ml*	(Pathavi, 2019)
MF (TS 10-15%)	Solid State Anaerobic mono-digestion	Size reduction (1-5cm)	Anaerobic sludge	55	7±1.0	40	269.107 mL CH4/g VS	(25)
MF+ CM	Anaerobic co-digestion	Biological pretreatment	POME Sludge	Ambient temperature	7±1.0	30	69.3 ml CH_4/g VS	(25)
MF + EFB (50:50)	Co-digestion (semi batch fermentation refilled 0.3 g every 5 days)	Size reduction (10mm), NaOH 10% (30 min)	Waste water treatment sludge	60	7-8	30	222.28 ml CH_4/g VS	(38)

Table 2.7 Summary of methane yield of oil palm solid wastes at similar working conditions.

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref.
OPF (TS 16%)	Solid State Anaerobic mono-digestion	Oven dried (95°C for 48 h), Size reduction (5mm)	POME sludge	55	7±0.0	20	207 ml CH_4/g VS	(18)
EFB (TS 10-15%)	Solid State Anaerobic mono-digestion	Size reduction	Biogas Sludge	55	7±0.0	35	429 ml CH_4/g VS	(25)
DC+ 5% OPA (TS 15%)	Solid State Anaerobic mono-digestion	Pressurized steam (145°C), drying (105°C), Size reduction <2mm	Anaerobic sludge + POME sludge	55	7±0.0	60	160 ml CH_4/g VS	(22)
OPT (TS 16%)	Solid State Anaerobic mono-digestion	Oven dried (95°C for 48 h), Size reduction (5mm)	POME sludge	55	7±0.0	20	161 ml CH_4/g VS	(18)
MF (TS 10-15%)	Solid State Anaerobic mono-digestion	Size reduction (1-5cm)	Anaerobic sludge	55	7±1.0	40	269.107 mL CH4/g VS	(25)

Table 2.8 Summary of optimum methane production from oil palm solid wastes.

Substrate	Digestion method	Pretreatment	Inoculum Type	Temp (°C)	pH	Time (days)	Methane Yield	Ref.
OPF ethanol effluent	Wet anaerobic digestion	Size reduction and Co pretreatment: Water + Microwave	POME plant sludge	35	7.3 - 7.5	ND	514 ml CH_4/g VS	(21)
EFB (TS 10-15%)	Solid State Anaerobic mono-digestion	Size reduction	Biogas Sludge	55	7±0.0	35	429 ml CH_4/g VS	(25)
DC+ POME	Anaerobic digestion	Size reduction	Biogas sludge	60	7±0.0	45	613 ml CH_4/g VS.	(26)
OPTr + POME hydrolysate	Anaerobic co-digestion	Size reduction, Sun dried, Oven dried (68°C), Crude enzyme	Anaerobic sludge + POME	37	7±0.1	30	369±6.10 mL CH4/g VS	(34)
MF	Anaerobic mono-digestion	Size reduction (1-5cm)	Anaerobic sludge	55	7±1.0	40	269.107 mL CH4/g VS	(25)

From the available oil palm solid waste, OPF has the highest contribution of the total solid waste with 38%. This shows that OPF has the potential to be used for biogas and bioethanol production and will increase their added value, which could help Indonesia reach the goal of 23% renewable energy by 2025

REFERENCES

[1] E.M. Clarke, E.A. Emerson, Design and synthesis of synchronization skeletons using branching time temporal logic, in: D. Kozen (Eds.), Workshop on Logics of Programs, Lecture Notes in Computer Science, vol. 131, Springer, Berlin, Heidelberg, 1981, pp. 52–71. DOI: https://doi.org/10.1007/BFb0025774

[2] J.P. Queille, J. Sifakis, Specification and verification of concurrent systems in CESAR, in: M. Dezani-Ciancaglini and U. Montanari (Eds.), Proceedings of the 5th International Symposium on Programming, Lecture Notes in Computer Science, vol. 137, Springer, Berlin, Heidelberg, 1982, pp. 337–351. DOI: https://doi.org/10.1007/3-540-11494-7_22

[3] C. Baier, J-P. Katoen, Principles of Model Checking, MIT Press, 2008.

[4] M. Kwiatkowska, G. Norman, D. Parker, Stochastic model checking, in: M. Bernardo, J. Hillston (Eds.), Proceedings of the Formal Methods for the Design of Computer, Communication and Software Systems: Performance Evaluation (SFM), Springer, Berlin, Heidelberg, 2007, pp. 220–270. DOI: https://doi.org/10.1007/978-3-540-72522-0_6

[5] V. Forejt, M. Kwiatkowska, G. Norman, D. Parker, Automated verification techniques for probabilistic systems, in: M. Bernardo, V. Issarny (Eds.), Proceedings of the Formal Methods for Eternal Networked Software Systems (SFM), Springer, Berlin, Heidelberg, 2011, pp. 53–113. DOI: https://doi.org/10.1007/978-3-642-21455-4_3

[6] G.D. Penna, B. Intrigila, I. Melatti, E. Tronci, M.V. Zilli, Bounded probabilistic model checking with the muralpha verifier, in: A.J. Hu, A.K. Martin (Eds.), Proceedings of the Formal Methods in Computer-Aided Design, Springer, Berlin, Heidelberg, 2004, pp. 214–229. DOI: https://doi.org/10.1007/978-3-540-30494-4_16

[7] E. Clarke, O. Grumberg, S. Jha, et al., Counterexample-guided abstraction refinement, in: E.A. Emerson, A.P. Sistla (Eds.), Computer Aided Verification, Springer, Berlin, Heidelberg, 2000, pp. 154–169. DOI: https://doi.org/10.1007/10722167_15

[8] H. Barringer, R. Kuiper, A. Pnueli, Now you may compose temporal logic specifications, in: Proceedings of the Sixteenth Annual ACM Symposium on the Theory of Computing (STOC), ACM, 1984, pp. 51–63. DOI: https://doi.org/10.1145/800057.808665

[1] IEA. Global energy demand rose by 2.3% in 2018, its fastest pace in the last decade - News - IEA [Internet]. INTERNATIONAL ENERGY AGENCY. 2019 [cited 2020 Nov 5]. Available from: https://www.iea.org/news/global-energy-demand-rose-by-23-in-2018-its-fastest-pace-in-the-last-decade

[2] OECD. World Energy Outlook 2020 – Analysis [Internet]. OECD International Energy Agency. 2020. p. 56–7. Available from: https://www.iea.org/reports/world-energy-outlook-2020

[3] Schiffer H-W, Kober T, Panos E. World Energy Council's Global Energy Scenarios to 2060 Perspektiven der weltweiten Energieversorgung bis 2060 – Die Szenarien des World Energy Councils. Zeitschrift für Energiewirtschaft. 2018;42(2):91–102.

[4] Lindgren G. Impending world oil shortage.

[5] Global Greenhouse Gas Emissions Data | Greenhouse Gas (GHG) Emissions | US EPA [Internet]. [cited 2020 Nov 3]. Available from: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

[6] BP Energy Outlook. BP Energy Outlook 2019 edition The Energy Outlook explores the forces shaping the global energy transition out to 2040 and the key uncertainties surrounding that. BP Energy Outlook 2019. 2019;

[7] IEA. The outlook for biogas and biomethane to 2040 – Outlook for biogas and biomethane: Prospects for organic growth – Analysis - IEA [Internet]. IEA (2020), Outlook for biogas and biomethane: Prospects for organic growth, IEA. 2020 [cited 2020 Nov 3]. Available from: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/the-outlook-for-biogas-and-biomethane-to-2040

[8] HOMEBIOGAS inc. Advantages and Disadvantages of Biogas | Homebiogas | Household Biogas Digester System [Internet]. 2020 [cited 2020 Nov 4]. Available from: https://www.homebiogas.com/Blog/141/Advantages_and_Disadvantages_of_Biogas

[9] Arnott, Michael;Dr. Alfredo S. Mercado; Dra. Lolita L. Mercado; Engineer Patricio M. Bael J. PT. The biogas/biofertilizer business handbook Chapter three: The raw materials of biogas digestion [Internet]. 1998 [cited 2020 Nov 4]. Available from: http://www.nzdl.org/gsdlmod?e=d-00000-00---off-0hdl--00-0----0-10-0---0---0direct-10---4-------0-1l--11-en-50---20-about---00-0-1-00-0--4----0-0-11-

10-0utfZz-8-00&cl=CL1.2&d=HASHe1ac42117320f176ac694c.6&gt=1

[10] MUNDI I. Palm Oil Production by Country in 1000 MT - Country Rankings [Internet]. INDEX MUNDI. 2021 [cited 2021 Jun 1]. Available from: https://www.indexmundi.com/agriculture/?commodity=palm-oil&graph=production

[11] Dungani R, Aditiawati P, Aprilia S, Yuniarti K, Karliati T, Suwandhi I, et al. Biomaterial from Oil Palm Waste: Properties, Characterization and Applications. In: Palm Oil [Internet]. InTech; 2018 [cited 2020 Nov 4]. Available from: http://dx.doi.org/10.5772/intechopen.76412

[12] Ritchie H. Energy mix - Our World in Data [Internet]. 2020 [cited 2021 Mar 21]. Available from: https://ourworldindata.org/energy-mix

[13] Sarker S, Lamb JJ, Hjelme DR, Lien KM. A review of the role of critical parameters in the design and operation of biogas production plants. Vol. 9, Applied Sciences (Switzerland). MDPI AG; 2019.

[14] Dani S, Wibawa A. CHALLENGES AND POLICY FOR BIOMASS ENERGY IN INDONESIA. Int J Business, Econ Law. 2018;15.

[15] Hambali E, Rivai - M. IOP Conference Series: Earth and Environmental Science The Potential of Palm Oil Waste Biomass in Indonesia in 2020 and 2030. 2017;

[16] Rasi S, Veijanen A, Rintala J. Trace compounds of biogas from different biogas production plants. Energy. 2007;32(8):1375–80.

[17] Hambali E, Rivai M. The Potential of Palm Oil Waste Biomass in Indonesia in 2020 and 2030. IOP Conf Ser Earth Environ Sci. 2017;65(1).

[18] Suksong W, Jehlee A, Singkhala A, Kongjan P, Prasertsan P, Imai T, et al. Thermophilic solid-state anaerobic digestion of solid waste residues from palm oil mill industry for biogas production. Ind Crops Prod [Internet]. 2017;95:502–11. Available from: http://dx.doi.org/10.1016/j.indcrop.2016.11.002

[19] Nurdin IA, Syauqi A, Laili S. Pengukuran Rasio C/N pada Campuran Daun Kelapa Sawit (Elaeis guineensis Jacq.) dan Feses Sapi (Bos taurus L.) dalam Fermentasi Biogas. J SAINS ALAMI (Known Nature). 2020;3(1):29–36.

[20] Samuel O. Comparative Evaluation of Qualitative and Quantitative Biogas Production Potential of Oil Palm Fronds and Co-digestion with Cow Dung. 2013;3(4):25–34.

[21] Srirnachai T, Thonglimp V, O-Thong S. Ethanol and methane production from oil palm frond by two stage ssf. Energy Procedia [Internet]. 2014;52:352–61. Available from: http://dx.doi.org/10.1016/j.egypro.2014.07.086

[22] Tepsour M, Usmanbaha N, Rattanaya T, Jariyaboon R, O-Thong S, Prasertsan P, et al. Biogas Production from Oil Palm Empty Fruit Bunches and Palm Oil Decanter Cake using. Energies. 2019;12(4368):1–14.

[23] Saelor S, Kongjan P, O-Thong S. Biogas Production from Anaerobic Co-digestion of Palm Oil Mill Effluent and Empty Fruit Bunches. Energy Procedia [Internet]. 2017;138:717–22. Available from: https://doi.org/10.1016/j.egypro.2017.10.206

[24] Rosada H. Co-Digestion Of Cow Manure And Empty Fruit Bunches : Effect Of C / N Ratio And Kinetic Studies. 2018;13(9):7052–8.

[25] Wadchasit P, Siripattana C, Nuithitikul K. The effect of pretreatment methods for improved biogas production from oil-palm empty fruit bunches (EFB): Experimental and model. IOP Conf Ser Earth Environ Sci. 2020;463(1).

[26] Kanchanasuta S, Pisutpaisal N. Waste utilization of palm oil decanter cake on biogas fermentation ScienceDirect Waste utilization of palm oil decanter cake on biogas fermentation. Int J Hydrogen Energy [Internet]. 2016;(July). Available from: http://dx.doi.org/10.1016/j.ijhydene.2016.04.129

[27] Khairul Anuar N, Che Man H, Idrus S, Nik Daud NN. Biochemical methane potential (BMP) from anaerobic co-digestion of sewage sludge and decanter cake. IOP Conf Ser Mater Sci Eng. 2018;368(1).

[28] Wattanasit K, Asawatreratanakul K, O-thong S. Potential of Biogas Production of Oil Palm Mill Residues and its Anaerobic Co-digestion under Thermophilic Conditions. 2013;(3).

[29] S J Malik | Aparna Saraf | Srinivas Kasulla. Biogas Production from Decanter Cake of Palm Oil Mill from South India. 2020;(January 2021):1144–7.

[30] Kaosol T, Rungarunanotai W. Effect of microwave pretreatment on BMP of decanter cake from palm oil mill factory. Am J Appl Sci. 2016;13(5):609–17.

[31] Kaosol T, Sohgrathok N. Enhancement of biogas production potential for anaerobic co-digestion of wastewater using decanter cake. Am J Agric Biol Sci. 2013;8(1):67–74.

[32] Rongwang C, Polprasert S, Kanchanasuta S. Effect of partial ozonation and thermal pretreatment on

biogas production from palm oil decanter cake. Chem Eng Trans. 2017;57:1987–92.

[33] Sitthikitpanya S, Reungsang A, Prasertsan P. Two-stage thermophilic bio-hydrogen and methane production from lime-pretreated oil palm trunk by simultaneous saccharification and fermentation. Int J Hydrogen Energy. 2018;43(9):4284–93.

[34] Nutongkaew T, Prasertsan P, O-Thong S, Chanthong S, Suyotha W. Improved Methane Production Using Lignocellulolytic Enzymes from Trichoderma koningiopsis TM3 Through Co-digestion of Palm Oil Mill Effluent and Oil Palm Trunk Residues. Waste and Biomass Valorization [Internet]. 2020;11(10):5123–36. Available from: https://doi.org/10.1007/s12649-019-00838-z

[35] Chaikitkaew S, Kongjan P, O-Thong S. Biogas Production from Biomass Residues of Palm Oil Mill by Solid State Anaerobic Digestion [Internet]. Vol. 79, Energy Procedia. Elsevier B.V.; 2015. 838–844 p. Available from: http://dx.doi.org/10.1016/j.egypro.2015.11.575

[36] Saidu M, Yuzir A, Salim MR, Salmiati, Azman S, Abdullah N. Biological pre-treated oil palm mesocarp fibre with cattle manure for biogas production by anaerobic digestion during acclimatization phase. Int Biodeterior Biodegrad [Internet]. 2014;95(PA):189–94. Available from: http://dx.doi.org/10.1016/j.ibiod.2014.06.014

[37] Saidu M, Yuzir A, Salim MR, Richard A, Afiz B. Effect of operating parameter on the anaerobic digestion oil palm mesocarp fibre with cattle manure for biogas production. IOP Conf Ser Earth Environ Sci. 2020;476(1).

[38] Chaipa S, Asavavisithchai S. Biogas production from palm fibers together with empty palm bunches using microbial sludge from anaerobic wastewater treatment system. 2016;1597–604.

[39] Putri MP. ALKALINE PRETREATMENT OF OIL PALM LIGNOCELLULOSIC WASTE FOR BIOGAS PRODUCTION UNDER WET AND SOLID STATE FEMENTATION. TAPPI J. 2018;17(07):69.

[40] Suksong W, Promnuan K, Seengenyoung J, O-Thong S. Anaerobic Co-Digestion of Palm Oil Mill Waste Residues with Sewage Sludge for Biogas Production. Energy Procedia [Internet]. 2017;138:789–94. Available from: https://doi.org/10.1016/j.egypro.2017.10.06

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